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THE 0.1m. SUBSONIC CRYOGENIC TUNNEL AT THE UNIVERSITY OF SOUTHAMPTON

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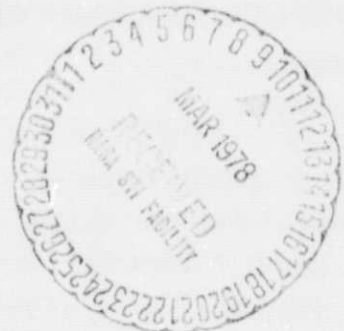
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The use of trade names in this paper is essential to a proper understanding of the subject material; their use in no way implies endorsement.

ABSTRACT

The design and performance of a low speed one-atmosphere cryogenic wind tunnel is described. The tunnel is fan driven and operates over the temperature range 305K to 77K at Mach numbers up to 0.28. It is cooled by the injection and evaporation of liquid nitrogen in the circuit, and the usual test gas is nitrogen.

The tunnel has a square test section 0.1m. across and was built to allow, at low costs, the development of testing techniques and the development of instrumentation for use in cryogenic tunnels, and to exploit in general instrumentation work the unusually wide range of unit Reynolds number available in such tunnels. The tunnel was first used in the development of surface flow visualization techniques for use at cryogenic temperatures.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The wind tunnel described in this report was designed to provide the means for aerodynamic testing at cryogenic temperatures and at low cost. Both the constructional and the running costs were to be held to a practical minimum while allowing specific types of research and development work to be performed. The classes of work for which the tunnel was constructed included the development of surface flow visualization techniques and also specialised instrumentation for use at cryogenic temperatures, the development and evaluation of general purpose instrumentation over a wide range of unit Reynolds numbers, and investigations into the problems of coupling a cryogenic tunnel to a magnetic suspension and balance system.

A tunnel featuring a small test section and operation at atmospheric pressure would provide conditions suitable for these classes of investigation, features which combine to minimize costs. A continuous running tunnel was chosen because:

- i) operational procedures for such tunnel are already well established,
- ii) inexpensive tunnel instrumentation may be used,
- iii) long run times are required to allow tracers to reveal details of surface flow patterns,
- iv) the existing magnetic suspension system^{1,2} was best suited to continuously running tunnels.

The choice of maximum operating Mach number was rather arbitrary. While much useful work can be done in test section flows limited to very low Mach numbers, the useful range of variation in air speed is then restricted by the resolving power of the instrumentation. In the evaluation of general purpose instrumentation of the pressure probe type where performance is a function of Reynolds number and Mach number there is a requirement for varying both parameters over wide ranges. It was felt that a tunnel allowing compressibility effects to be investigated would be too expensive, and therefore the tunnel was designed for a maximum test section Mach number which would allow testing over as wide a range of "incompressible" speeds as practically possible. As some types of pressure probes have quite low critical Mach numbers (on a circular cylinder in cross flow this is around 0.4) a maximum Mach number of about 0.35 was chosen.

There is an unusually wide range of unit Reynolds number available in cryogenic tunnels with these specifications. The extremes of the ranges are produced in the following manner. The low end is obtained when the lowest practical Mach number is combined with the maximum test temperature, and the high end when the highest Mach number is combined with the minimum temperature. The lowest practical Mach number might be about 0.04 with conventional instrumentation, leading to a more than 50:1 range of unit Reynolds number when operating over this Mach number range and between the temperature limits of 300K and about 78K. The range of Reynolds number can be further extended, perhaps to 200:1, by changing the size of model.

The test section is the minimum practical size which would satisfy requirements, and is square, 101.6mm. (4 inches) from wall to wall at its upstream end, with 45° fillets extending 12.7mm. (0.5 inch) from the corners. The resultant flow area is 0.01m.² and the effective height of the test section ($\sqrt{\text{area}}$) is therefore 0.1m. The following sections describe the tunnel and its performance, as designed to these guidelines.

2. AERODYNAMIC LINES AND PREDICTED OPERATING ENVELOPE

2.1 Aerodynamic Lines

Considerations of economies in construction and operation were allowed to dominate the choice of the lines of the tunnel, simply because its duties were not demanding of the highest quality of test section flow. A closed circuit is a necessary feature of a fan driven cryogenic wind tunnel, and a low constructional cost is obtained by the choice of a compact circuit.

Operating costs are dominated by the cost of liquid nitrogen, LN_2 , the consumption of which depends partly on the heat leakage from the room into the circuit which is minimized by circuit compactness and the use of good thermal insulation, and depends partly on the power input to the circuit from the fan drive motor. The latter is minimized by the choice of an efficient fan and a circuit having low losses of stagnation pressure across its various components.

The principal components contributing to circuit pressure losses are diffusers, corners, and the screen. Diffuser losses are minimized by the use of suitably small angles, and therefore the diffusers in this tunnel have included angles of about $4\frac{1}{2}^\circ$. The area ratio of the first diffuser is 2.1:1 and of the second 1.74:1, giving geometries which conform to good diffuser practice. The aerodynamic lines and key dimensions are shown in Figure 1. Corners of simple design were chosen containing vanes with low loss characteristics. The vanes were circular arcs centered on a common point. With this design loss of stagnation pressure around each channel formed by adjacent vanes depends

principally on the ratio of the outside to inside radii of the channel. For approximately constant loss around each channel a constant ratio of outer to inner radius was chosen, leading to vanes having radii in geometric progression. At the small end of the tunnel there are three channels each with a radius ratio of 1.62, and at the big end the geometric progression vanes form five channels each with a radius ratio of 1.4. The estimated losses around the channels³ lie in the range 10% to 15% of the local dynamic pressure.

There can be large spacial variations in velocity downstream of this type of corner vane. References 3 and 4 indicate a need for a pressure drop across the smoothing screen amounting to between 2 and 4 times the local dynamic head, in order to remove steady spacial variations in velocity. A single screen was chosen for this purpose having a wire diameter of 0.229mm. (0.009 inch) in a square weave at pitch 0.635mm. (0.025 inch). Immediately ahead of the screen is a very short wide-angled diffuser, area ratio 1.04:1, and downstream is a 5.4:1 contraction leading to the test section.

The circuit is generally square in cross section but with the following exceptions. Developing inside the contraction, running through the test section, and then blending into the first diffuser corners is a 45° corner fillet. The circuit cross section is circular at the fan and also through the nacelle, with a square-to-round adapter between the small end corner and fan. The second diffuser returns the circular cross section to square at entry to the big end corner vanes.

2.2 Operating Envelope

General performance curves for atmospheric pressure low speed cryogenic nitrogen tunnels are given on Figure 2, which shows unit Reynolds number in the test section as a function of Mach number and stagnation temperature T_0 . The range in T_0 , from about 77K to 300K, has its extremes set by practical considerations. The lower limit is set by the gas properties in the test section reaching the saturation boundary for N_2 (the free stream saturation line FSS on Figure 2) and the upper limit by a typical room temperature. It would be fairly easy to design a tunnel to operate at temperatures up to 400K, but the only reason for doing so seems to be to raise the ratio of maximum to minimum achievable Reynolds numbers. Furthermore the cost and complexity of such a tunnel would be increased because of the probable need for a heater, otherwise even in the case of a well insulated and uncooled tunnel there would be a long delay in waiting for the fan drive power of a low speed tunnel to raise the circuit temperature to such a level. Although the ratio of maximum to minimum Reynolds numbers would then be about 80:1 for this type of low speed tunnel, the extension in the range would be downward rather than the other and perhaps more useful direction. It was decided therefore to omit a heater and to run at temperatures up to only about 300K.

The minimum practical operating temperature shown on Figure 2 as the FSS line was chosen following a report⁵ of satisfactory airfoil behaviour at these conditions. At the anticipated maximum test section Mach number of 0.35 the unit Reynolds number becomes 49.3×10^6 per meter. The minimum

practical Reynolds number at 300K and a Mach number of 0.04 is 0.91×10^6 per meter giving a ratio of maximum to minimum usable Reynolds numbers of 54:1.

Superimposed on the general map on Figure 2 is further information applicable only to the 0.1m. tunnel, including the estimated power requirement for the fan which indicates that 1.4kW is just sufficient for Mach 0.35 at the lowest attainable temperature, whereas about 2.5kW would be required at room temperature. Stress limits in any fan will impose a maximum rotational speed limit, and through this a maximum velocity in the test section. This translates into an upper Mach number boundary which is a strong function of stagnation temperature T_0 because of the dependence of speed of sound on temperature. The estimated position of this boundary is shown on Figure 2 for the design of fan adopted for the 0.1m. tunnel, which was stress limited to 6,000 r.p.m. A restriction of this type imposes a severe cut-off in terms of attainable test section Mach number at the higher temperatures.

The operating envelope for an atmospheric pressure 0.1m. cryogenic tunnel subject to the above limitations in speed and temperature is roughly triangular, bounded by the FSS line, the fan stress limit line, and the maximum temperature line. The two corners of the triangular boundary at the extreme ends of the fan speed limit line have the following properties:

Temperature T_0 , K	300	78.6
Mach no.	0.16	0.36
Fan power, kW	0.5	1.4
Reynolds no./m. (millions)	3.6	49.3

A 1½kW motor was therefore chosen to allow operation over the entire envelope.

3. DESIGN FEATURES

3.1 General

The principal materials of construction of the circuit including the fan and nacelle sections are (1) aluminum (when used in sheet form it was 1.59mm. (1/16 inch thick) with welded aluminum flanges 6.35mm. (1/4 inch) thick), and (2) fiberglass with fiberglass flanges 4.76mm. (3/16 inch) thick.

The flanges are sealed with a self curing silicone rubber (Dow Corning bathtub caulk) and bolted with brass nuts and bolts. The driveshaft and some bolts in the fan and bearing area are stainless steel, and also a traversing probe in the test section. Copper and brass components are used in the screen area, LN₂ supply and spray, the gaseous nitrogen vent system, and static pressure measuring ports. A phenolic-bonded fabric laminate (Tufnol) is used in two places as a thermal barrier. There are glass windows in the test section. The permanent joints have been made by welding, silver and soft solder, and epoxy glue. All of the above materials have proved satisfactory.

3.2 Thermal Insulation

The nature of the tests to be undertaken in this tunnel required that the operating temperature should be capable of fairly rapid change. Regulation of the rate of injection of LN₂ very effectively controls the cooldown rate, but a responsive tunnel requires also an adequate warmup rate. As no heater is fitted and the energy input from the fan of a low speed

atmospheric tunnel is quite small, it was seen as a requirement for this tunnel that any insulation applied to the outer shell should still allow sufficient heat leakage to raise the circuit temperature at a reasonable rate.

In the event the exterior was insulated using a variety of types of insulation. The nacelle section, the second diffuser, and the roof of the test section were insulated with a 14mm. (0.56 inch) thick layer of foam rubber sheet, the outer surface of the sheet being impervious to water. This insulation was not entirely satisfactory in this application because of the formation of frost during lengthy runs.

The outside curve and top of the big end of the circuit was insulated with a 25mm. (1 inch) thick sheet of the same material, proving quite satisfactory in that neither frost nor dew was evident.

The first diffuser was first insulated with fiberglass 76mm. (3 inches) thick contained in plastic bags (an insulation material designed for the outside of hot water cylinders) which proved satisfactory as an insulation but bulky and otherwise inconvenient for the tunnel application. It was replaced by a two-layer insulation comprising an inner layer of 12mm. ($\frac{1}{2}$ inch) styrofoam and an outer layer of bubbled polyethylene sheet of the type used for packing instruments for transportation (Aircap SD-240, Sealed Air Corp.). This combination was quite satisfactory as an insulation.

The remainder of the circuit was uninsulated, and therefore developed a thick layer of frost during low temperature

runs. The presence of a large area of frost is in itself not an inconvenience, but may be undesirable because of the formation of moisture during the warm-up of the tunnel, and because of an unnecessarily high LN_2 consumption.

3.3 The Test Section

This is 254mm. (10 inches) long and 101.6mm. (4 inches) square at its upstream end, diverging slightly to allow for boundary-layer development. The walls are 11.1mm. (7/16 inch) thick aluminum, and are pierced for a 76.2 x 127mm. (3 x 5 inch) detachable floor, and pierced for windows in one side and the top. A cross section at the windows is shown in Figure 3(a). The glass disk in the sidewall is 12.7mm. ($\frac{1}{2}$ inch) thick, bevelled at 45° , and retained only by a bolted ring. A 240 volt, 25 watt lamp contained in an aluminum box illuminates the interior of the test section. The box keeps the window free from moisture and frost.

The viewing window on the top of the test section is also circular, and quadruple glazed to allow its outer layer, exposed to the room, to remain clear. The inner layer of glass is 6mm. (0.236 inch) thick and 76.2mm. (3 inch) diameter, and is bonded with epoxy directly to the aluminum roof. The three outer layers are 98.3mm. (3.87 inch) diameter and 4mm. (0.157 inch) thick, with a hole 3.17mm. ($\frac{1}{8}$ inch) diameter pierced through two of them. They are contained in an aluminum frame, the innermost of the 4mm. glasses and the frame each seating on a Tufnol insulating ring separating them from the test section. The outer two glasses are separated by O-rings, and

all of the 4mm. glasses are retained in the frame by a spring clip. Dry nitrogen gas from a storage bottle at room temperature is passed to the window frame along a 6.35mm. ($\frac{1}{4}$ inch) outside diameter copper tube. The gas flows through the inter-glass layers and out to the room as shown on Figure 3(a), keeping the window entirely clear.

At the upstream end of the test section is a traversing probe system, shown in Figure 3(a) and 3(b), and at each end of the roof are two static tapings. One tapping is shown again on Figure 3(c). The instrumentation is discussed more fully in Section 4.

3.4 The Nitrogen System

Liquid nitrogen is stored in a 169 liter vacuum insulated dewar (Union Carbide type PGS-45) with an automatic self-pressurizing system, and with provision for gas or liquid N₂ take-offs. The dewar carries its own control valves, which are used for regulating gas or liquid flows to the tunnel. The dewar is connected to the tunnel by a 9.5mm. ($\frac{3}{8}$ inch) diameter copper tube about 1.2m. (4 feet) long, insulated on its outside by a tube of foam rubber (Armstrong Armaflex) with wall thickness 9mm. (0.35 inch), covered by an additional layer of approximately 12mm. ($\frac{1}{2}$ inch) thick fiberglass. The outside of this insulation remained dry.

Liquid or gaseous nitrogen (depending on the stage reached during tunnel operation) are sprayed into the circuit through three holes 1.98mm. ($\frac{5}{64}$ inch) diameter drilled into the trailing edge of a 4.3mm. (0.17 inch) inside diameter tube almost

spanning the upstream end of the first diffuser, as shown on Figure 3(c). The spray and its fittings are brass, silver soldered.

A gaseous nitrogen vent is positioned just ahead of the big end turning vanes. The vent pipe is copper, 25.4mm. (1 inch) bore, with a brass butterfly valve in it to allow circuit pressurization or to prevent backflow of air to the tunnel. The vent pipe leads into the open air outside of the laboratory.

3.5 The Contraction and Screen

The cross section and co-ordinates of the fiberglass contraction are shown on Figure 4. The area ratio from screen to test section entrance is 5.42:1. The screen and its supporting frame are shown on Figure 5. The frame was folded from brass sheet 0.91mm. (0.036 inch) thick, and the joints silver soldered. The copper wire screen was soft soldered onto the frame. Pressure loss data on the screen is given in Section 5.

3.6 Bends, Diffusers

These were fabricated from 1.59mm. (1/16 inch) sheet aluminum, with continuously welded joints to exclude air and moisture. The turning vanes were tack-welded in place. The small end was pierced and one turning vane was cut away locally for the fan drive shaft. The cross sections of the ends are square throughout, 152.4mm. (6 inches) across at the small end and 228.6mm. (9 inches) across at the big end.

3.7 The Fan and Drive Shaft

The fan is driven from a $1\frac{1}{2}$ kW (2H.P.) synchronous three phase AC motor outside of the tunnel, with the power supplied from a variable transformer. The motor is mounted on an aluminum channel running under the return leg of the circuit. The tunnel is attached to the channel by a bracket welded to the nacelle section inline with the flow straightening stator vanes. A section of the fan is shown on Figure 6. The nacelle section comprises an aluminum outer tube 195.6mm. (7.70 inches) internal and 203.2mm. (8 inches) external diameters, supporting a hollow aluminum centerbody through the 8 welded stator vanes. The maximum diameter of the centerbody is 100.3mm. (3.95 inches). Cantilevered from the front of the centerbody is an aluminum fan bearing housing, fitted with a thermocouple for indicating bearing temperature. The bearing is the double-row self alining type, a standard stock item, retained by a circlip. The inner track of the bearing is bolted to the stainless steel drive shaft, and the bearing is positioned inside the fan hub directly under the blades in order to minimize the effects of shaft misalignment on blade tip clearance. The aluminum rotor blades are welded along both sides of the roots to an aluminum hub which in turn is bolted to the driveshaft.

The rotor shroud is fiberglass, also the square-to-round section joining the shroud to the small end. The shroud is tapered in its internal diameter from 198.1mm. (7.8 inches) at its upstream end to 195.6mm. (7.7 inches) at the nacelle.

The rotor blades and straightener vanes are untwisted, and cut from 3.17mm. (1/8 inch) sheet rolled initially to a

circle to give circular arc camber lines. The blade angles are given on Figure 7. There are nine rotor blades, eight straightener vanes. The root diameters are all 100.3mm. (3.95 inches). The rotor tip diametral clearance is approximately 0.76mm. (0.03 inches).

A portion of the driveshaft is shown on Figure 8, extending from the tunnel to a V-belt drive pulley and revolution counter. The tubular driveshaft passes inside an aluminum extension tube carrying at its outer end a roller bearing and oil seal inside an aluminum housing. The housing is nominally at room temperature. This arrangement allows the roller bearing to be conventionally lubricated, and the oil seal to remain flexible to exclude oil and moisture from the tunnel. Adjacent to the small end is Tufnol thermal barrier, to prevent the undue spread of frost along the extension tube. Under stabilised conditions frost extends approximately to the end of the thermal barrier further from the tunnel. The overall length of the extension tube including bearing housing is 417.2mm. (16.42 inches).

The weight of the wind tunnel, including driveshaft but excluding the drive motor and its support channel, is about 30kg. (65 lb.).

4. INSTRUMENTATION

The locations of instrumentation sensors are shown on Figure 9, their approximate positions being indicated by a numbering system. Pressures are measured on manometers, and most temperature measurements are made with copper/constantan thermocouples reading on a Comark type 1623 electronic thermometer gauge.

At station 1, close to the trailing edges of the big end turning vanes, static pressure is measured in the roof, and a copper constantan thermocouple is bonded to the inside floor to indicate wall temperature. The air or nitrogen stream temperature is also measured at this point with a platinum resistance thermometer with digital readout (Doric). At station 2 at the downstream side of the screen is a roof static pressure tapping, and an unshielded thermocouple suspended in the airflow about one inch from the top wall. There are roof static pressure tapings at stations 3 at the downstream end of the contraction and 5 just inside the entrance to the test section.

Station 4 is a traverser mounted halfway up the test section sidewall carrying interchangeable probes, either a static pressure tube or a combined total pressure tube and total temperature sensor. The latter is shown on Figures 3(a) and 3(b). Mechanical details of typical wall static tapings are shown on Figure 3(c), in this case tapings at stations 7 and 8. 3.17mm. (1/8 inch) outside diameter copper tubes leading to the manometers are silver-soldered to brass disks. The disks are screwed and glued with epoxy to the tunnel walls.

Where mounted on a thin tunnel wall the copper tube is fed through and cut off flush with the interior of the wall, otherwise the copper tube communicates with a small orifice drilled through the wall. Both variants appear on Figure 3(c).

A thermocouple is buried in the floor at station 6 approximately halfway along the test section, for use during the development of a surface flow visualization technique. At stations 10, 11 and 12 are wall static pressure, bearing temperature and wall static pressure sensors respectively. Finally at the warm end of driveshaft, station 9, is an electromagnetic pickup, sketched on Figure 8 and comprising a permanent magnet on the drive-shaft, a soft-iron horseshoe yoke and a coil. The voltage signal from the coil is approximately a square-wave varying linearly in amplitude with a calibration 0.00575 volts peak-to-peak per r.p.m. Readout is on a digital frequency meter.

If the wide range of Reynolds number potentially available from this type of cryogenic wind tunnel is to be fully exploited, the user must provide for adequate resolution of pressure over a wide range of Mach numbers and hence dynamic pressure. In this tunnel the dynamic pressure varies roughly as the square of Mach number, and the ratio of maximum to minimum usable Mach numbers is between 8 and 9 to 1, leading to a ratio of maximum to minimum dynamic pressures of about 75:1. Depending on the Mach number of the flow, pressures were therefore measured on alcohol or mercury manometers, in order to maintain adequate resolution over the wide range of dynamic pressures.

5. OPERATING PROCEDURE, MEASURED PERFORMANCE
AND A DISCUSSION OF POSSIBLE IMPROVEMENTS

5.1 Procedure

The tunnel was first run during February 1977, with its first cryogenic run on March 4, 1977. To the time of writing (November 1977) the total accumulated run time of 27 hours includes 554 minutes running below 150K and 378 minutes below 110K. During these runs (when the tunnel was used to develop a surface flow visualization technique using a propane-pigment suspension, work to be reported separately by D. Kell) the following operating procedures have gradually evolved, representing the current but not necessarily the best procedures.

Preparations for a tunnel run, additional to those special to the experiment being run in the test section, include a pressurization of the dewar to between 1 and 2 atmospheres (gauge), and feeding room temperature nitrogen from the gas bottle to the inter-glass layers in the viewing window.

Cooldown is initiated by valving liquid nitrogen to the spray, with the fan running at about 3000 r.p.m., and the vent valve open. Cooldown is rapid, the circuit gas temperature reaching the cryogenic range (150K) in about 12 minutes, and 100K in about 16 minutes. During the cooldown there are changing demands for motor power partly due to changing dynamic pressure, but in this tunnel due also to a stiffening of the grease in the fan bearing (during an early test with a bearing of the same type used dry but lubricated with powdered graphite, there had been a bearing failure resulting in a broken ball cage

and dulling of the surfaces of the balls and the tracks) which require attention if fan speed is to be held constant. During a cooldown at a constant high fan speed the changes in dynamic pressure can overload an alcohol manometer system. The circuit pressure is unsteady while LN_2 is being injected, particularly during cooldown when the LN_2 flow rates are high. The probable cause is partial vaporization in the dewar-to-tunnel supply pipe.

The circuit gas temperatures (as indicated by the traversing probe) can be held with practice to within $\pm 1^\circ\text{C}$ of a mean by control of LN_2 flow rate.

The warmup of the tunnel is not strongly influenced by fan speed, but is slightly faster with the fan on. The warmup time is about 45 minutes to room temperature.

A typical temperature-time trace is shown on Figure 10. The temperature was measured by the thermocouple at station 2 on Figure 9. The trace has automatic 15-minute markers, and a time scale has been added with its zero at a convenient marker. On this run the cooldown was initiated at time 2 minutes on this scale, the temperature reached 150K at time 15 minutes (13 minutes after initiation), and steadied at near liquid nitrogen temperature at time 30 minutes. Approximately half-an-hour was spent taking data close to this temperature, followed by a 5 minute period at about 100K and then a warmup. A photograph of the tunnel during a cryogenic run is reproduced on Figure 11. The principal features are the dewar and insulated supply pipe, the partially insulated and partly frost covered tunnel, and a frost-covered gaseous N_2 vent.

5.2 Measured Performance

Circuit performance data has been taken with a model present and with an empty test section. The latter is presented here. On Figure 12 is reproduced the unit Reynolds number/Mach number boundary for this tunnel from Figure 2. This is the cross-hatched boundary limited by maximum and minimum temperatures, and the fan stress limit. The fan has not yet been run to the stress limit because of the onset of unacceptable vibration, and the maximum speed is currently about 75% of the stress limited value. The experimental points on Figure 12 show the extremes of the envelope so far explored, and the tunnel can be operated anywhere inside the envelope defined by the experimental points. The maximum Mach number so far reached is 0.14 at room temperature, 0.28 at 80K, and the maximum unit Reynolds number is 39.6×10^6 per meter.

Static and total pressure measurements across the test section have been reduced and are presented as dimensionless plots of stagnation pressure and velocity distributions on Figure 13. The local stagnation pressure is P_o , and the centerline or reference value P_{o_r} . The centerline dynamic pressure and Mach number are q_r and M respectively. The stagnation pressure rises at the walls about 2% above its centerline value, and the velocity about 3%. This data was taken in air at room temperature.

Horizontal temperature distributions are given on Figure 14, taken at low temperature in nitrogen. There seems to be no systematic variation across the test section width; the standard deviations about the mean are:

Mean temperatureStandard deviation

K	K
79.4	.245
85.1	.306
110	.246

A non-dimensional measure of circuit losses is the ratio of static pressure rise across the fan to test section dynamic head. The fan pressure rise is taken as the difference between static pressures at stations 10 and 12, Figure 9. The flow areas at these stations are roughly equal at 232.2 sq.cm. (36 square inches) and 221.4 sq.cm. (34.31 square inches) respectively. The above non-dimensional ratio is given on Figure 15 as a function of unit Reynolds number in the test section. The data was taken over the usable ranges of circuit temperature and fan speed, and with an empty test section. The ratio of maximum to minimum Reynolds number shown here is over 40:1.

The ratio of pressure loss across the screen to the local dynamic pressure is given on Figure 16 as a function of Reynolds number R_d based on wire diameter. The pressure loss is close to expectations. Again the wide range of Reynolds number available from an unpressurized low speed cryogenic tunnel is very apparent.

There are five thermocouple stations indicated on Figure 9. Relative to the stream centerline stagnation temperature indicated by traverser 4, under equilibrium conditions numbers 2 and 11 were in agreement with no.4

within 1°K, no.6 in the test section floor was typically 12 degrees warmer and no.1 on the big end floor 20 or 30 degrees warmer except when puddling occurred in the big end. The possibility of puddling exists whenever circuit temperatures are brought close to LN₂ temperature, say close to 77K in this tunnel. There seem to be no adverse effects of puddling, for instance the test section flow is quite clear and dry, while an advantage to be gained from running with a small reservoir of LN₂ in the circuit is a stabilization of circuit temperature and pressure when the liquid supply from the dewar is turned off.

The 169 liter dewar provides nitrogen for the purge, cooldown and an adequate cryogenic running time of about 75 minutes. The length of run was noticeably dependent on the insulated area of the circuit. The rate of warmup is presently more than adequate, and therefore more insulation can be added allowing an extension of the run time.

Although this tunnel was designed for operation nominally at atmospheric pressure, as any tunnel structure will accommodate pressure changes to a limited extent, it has been lightly pressurised from time to time. The maximum static pressure in the big end so far recorded is 45cm. alcohol above atmospheric, giving a maximum absolute stagnation pressure of just over 1.034 atmospheres.

5.3 Possible Improvements

In its present form the tunnel can perform its duties reasonably well, but the following changes could be easily implemented and should improve its operation:

i) The fan should be balanced to reduce vibration at high speeds.

ii) The fan bearing should be replaced by a type designed specifically for operation in the cryogenic environment.

iii) Unsteadiness in circuit pressure should be reduced by improvements in the liquid supply system.

iv) Manometers should be replaced by a pressure transducer system in order to accommodate more conveniently the wide ranges of dynamic pressure.

v) More insulation should be added, perhaps to the extent of completely covering the outer surface of the tunnel.

6. CONCLUSIONS

1. The design, construction and operation of an atmospheric pressure low speed cryogenic tunnel are simple.

2. A wide variety of readily available materials may be used in its construction including plastics and metals. Inexpensive, compact and effective forms of insulation exist.

3. Wide ranges of unit Reynolds number are available at incompressible speeds in this type of tunnel.

4. Cooldown rates, temperature control and responsiveness when cold, and warmup rates are acceptable.

5. The rate of liquid nitrogen consumption is presently about 2½ liters per minute run time in the cryogenic temperature range, but may be reduced in future.

6. The aerodynamic performance of the circuit is good in terms of pressure losses, and the quality of test section flow is adequate for the purposes for which the tunnel was designed.

7. Improvements are seen to be possible and desirable. These include:

- (i) An increase of the maximum fan speed to its stress limited value.
- (ii) Replacement of the fan bearing by one designed specifically for use dry at cryogenic temperatures.
- (iii) The reduction of unsteadiness in the circuit pressure level.
- (iv) The use of alternate pressure transducers to accommodate the wide ranges of dynamic pressure.

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5. Hall, M.H., Ray, E.J. Investigation into Minimum Operating Temperatures for Cryogenic Wind Tunnels. AIAA Jnl. of Aircraft, Vol.14, no.6, June 1977.

DIMENSIONS : mm (inches)

1710.7 (67.35)

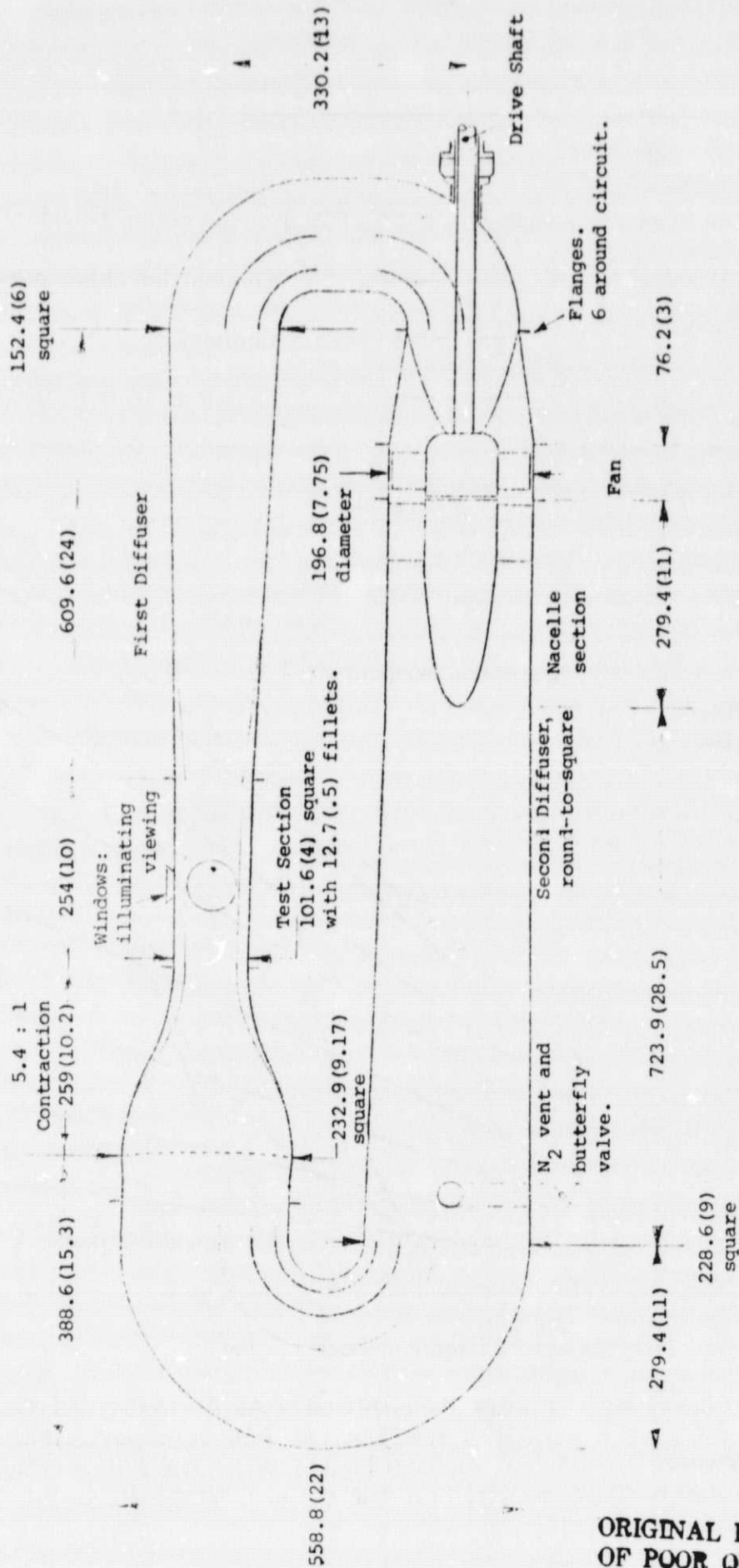


FIG 1. 0.1m CRYOGENIC WIND TUNNEL AT SOUTHAMPTON UNIVERSITY,
AERODYNAMIC LINES AND NOMINAL DIMENSIONS.

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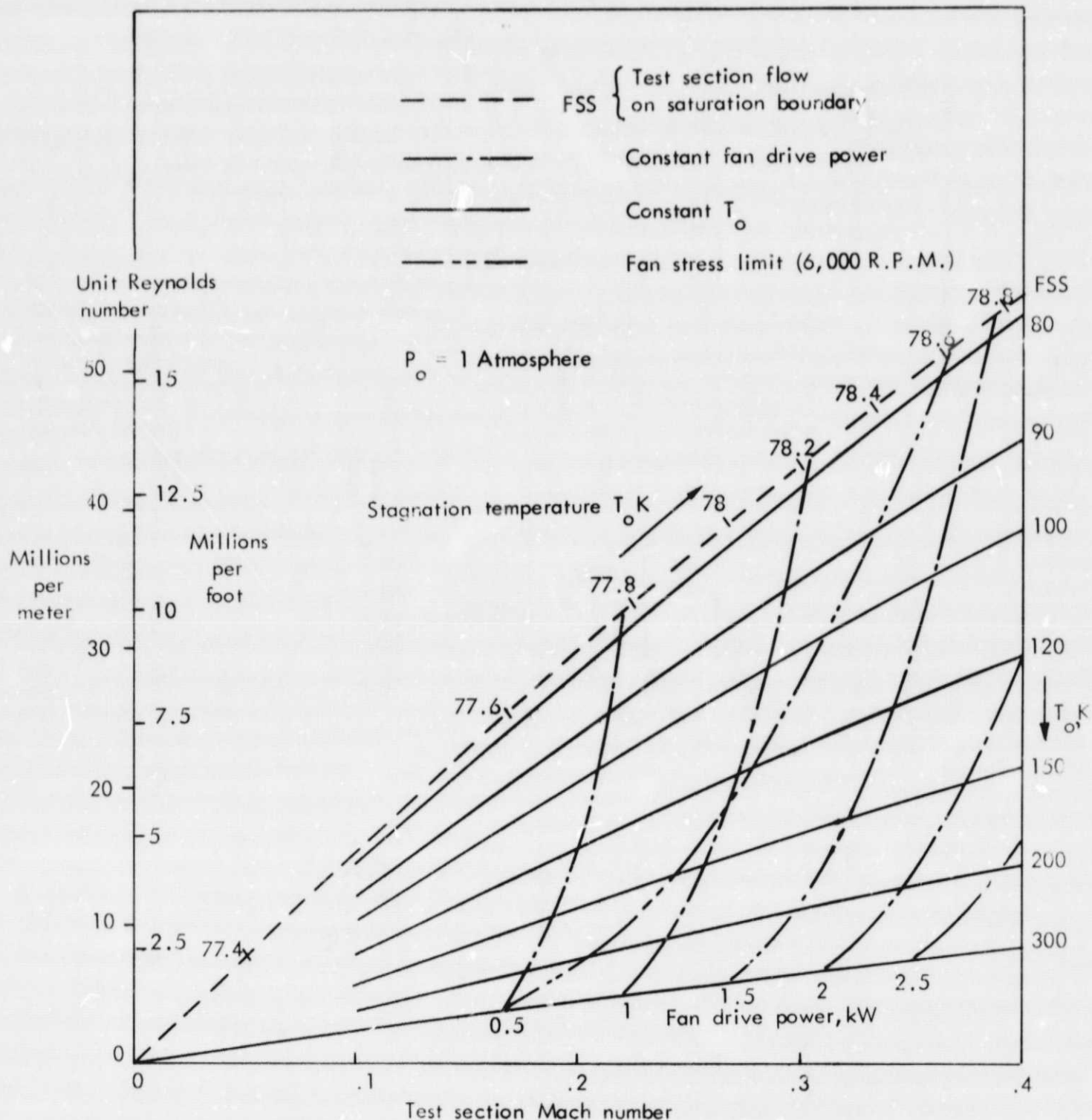
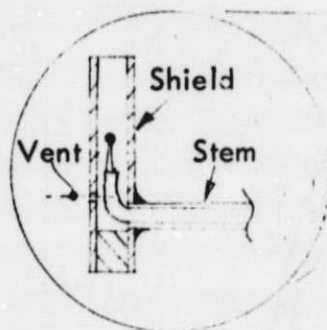
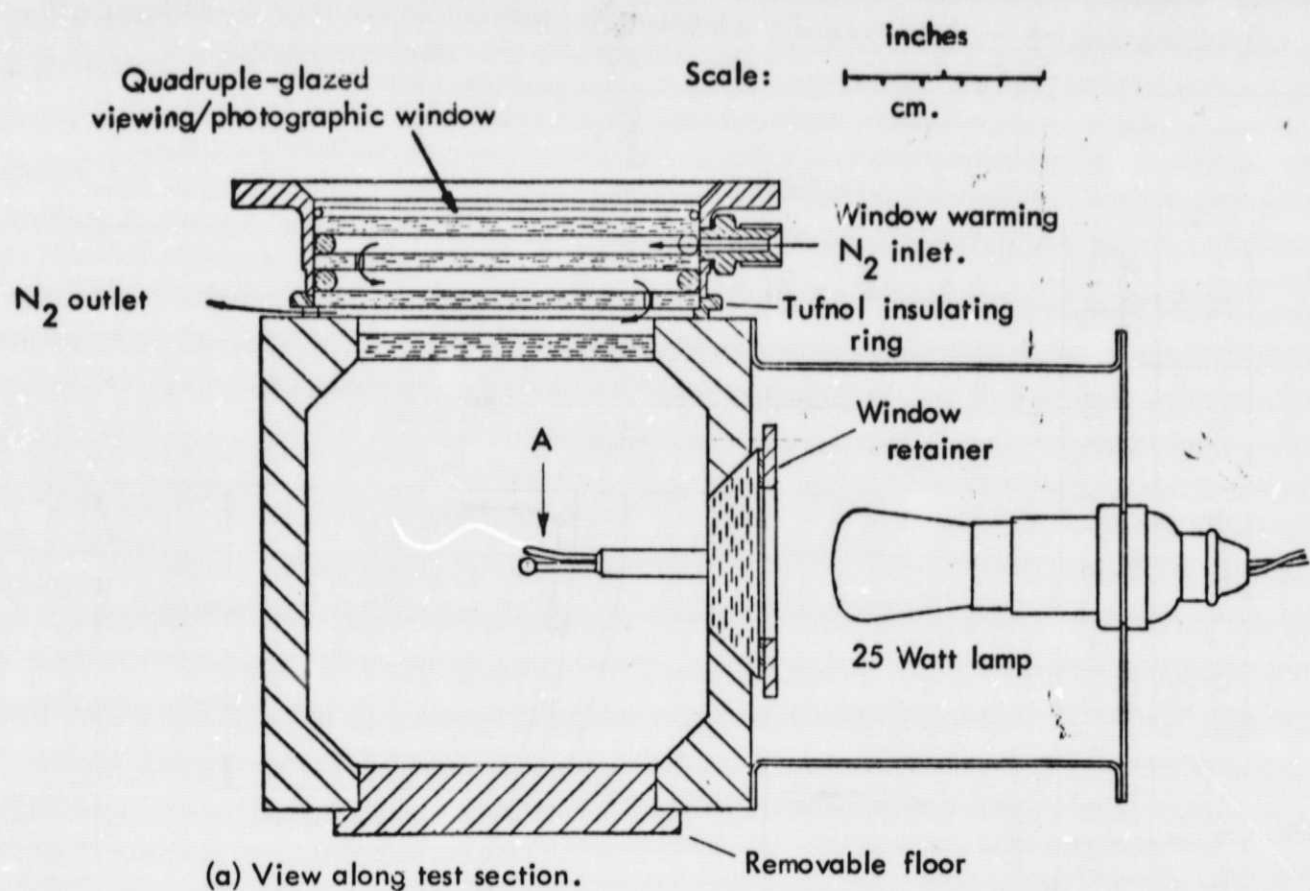
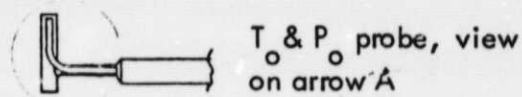


FIG 2. UNIT REYNOLDS NUMBER IN NITROGEN AS A FUNCTION OF MACH NUMBER AND STAGATION TEMPERATURE FOR LOW MACH NUMBER ATMOSPHERIC PRESSURE WIND TUNNELS, WITH THE FAN POWER REQUIREMENT AND SPEED LIMIT SHOWN FOR THE 0.1 m CRYOGENIC WIND TUNNEL



Enlarged cross section of shielded T_o probe



(b) Traversing probe details.

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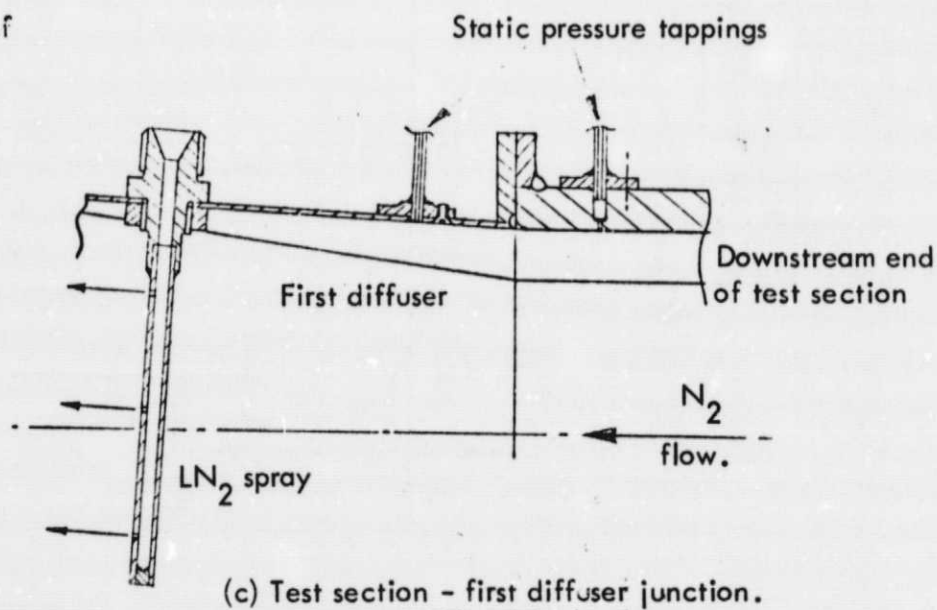


FIG 3. DETAILS IN REGION OF TEST SECTION.

X	0	25.4 (1)	50.8 (2)	76.2 (3)	101.6 (4)	127 (5)	152.4 (6)	177.8 (7)	203.2 (8)	228.6 (9)	254 (10)
Y	101.6 (4)	103.9 (4.09)	111.3 (4.39)	123.7 (4.87)	141.5 (5.57)	165.1 (6.5)	189.2 (7.45)	208 (8.19)	221.2 (8.71)	229.6 (9.04)	232.9 (9.17)

Dimensions: mm (inches)

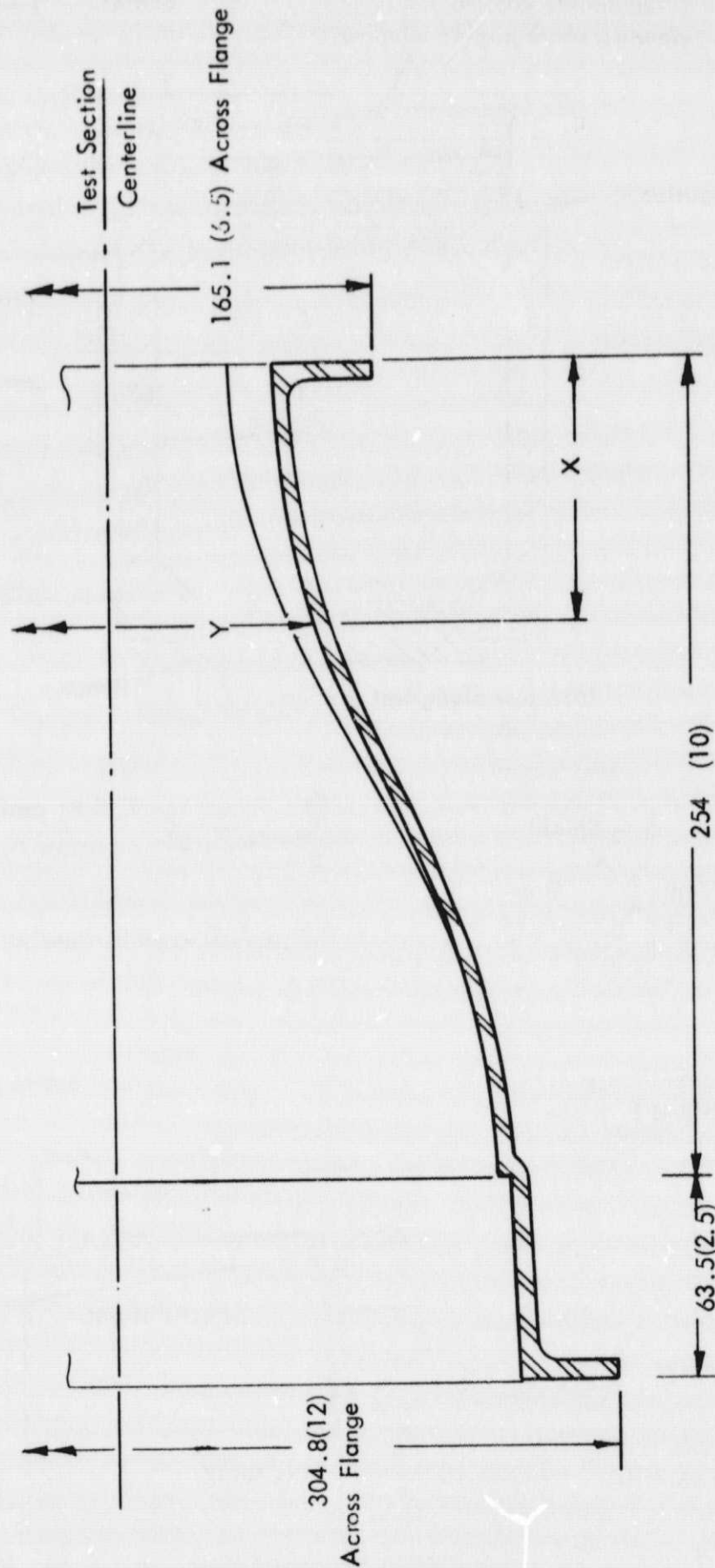


FIG 4. A PART CROSS-SECTION THROUGH THE FIBERGLASS CONTRACTION CONE, WITH PRINCIPAL DIMENSIONS

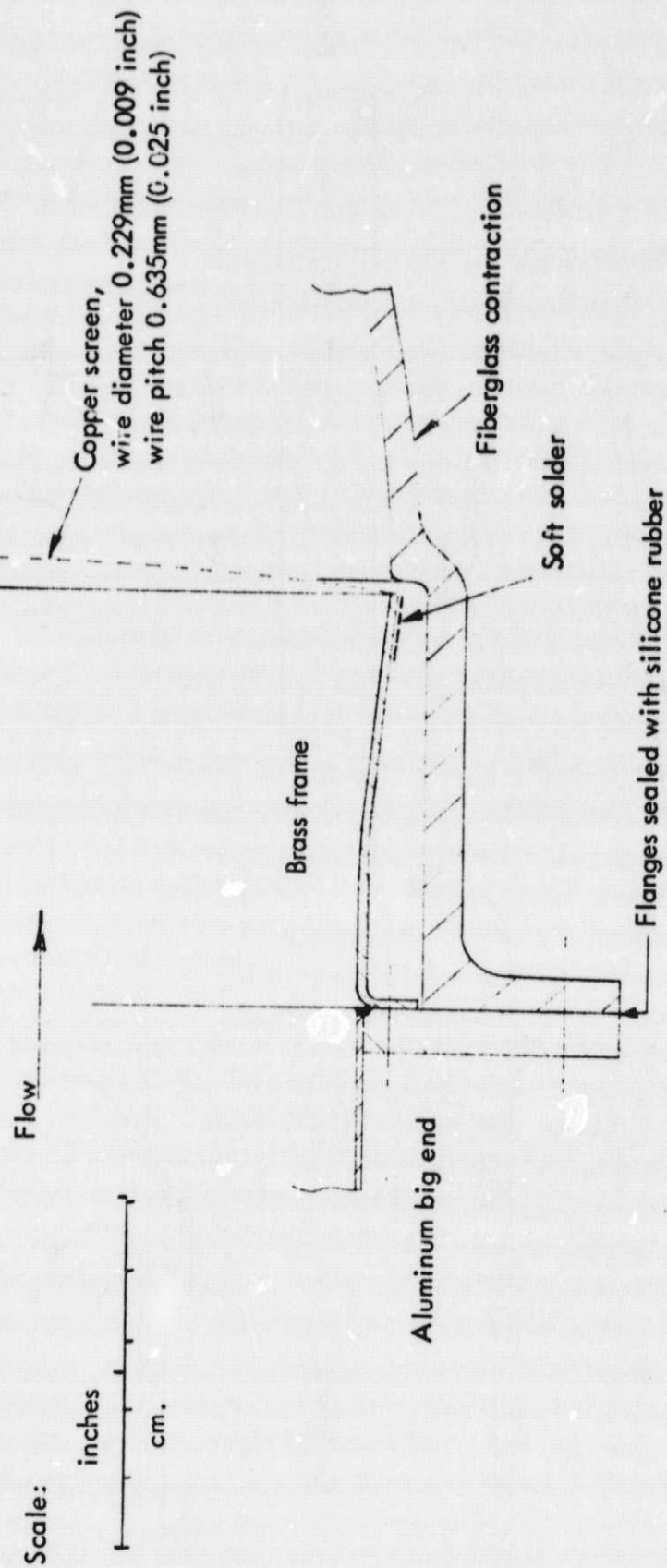


FIG 5. DETAILS IN REGION OF SCREEN.

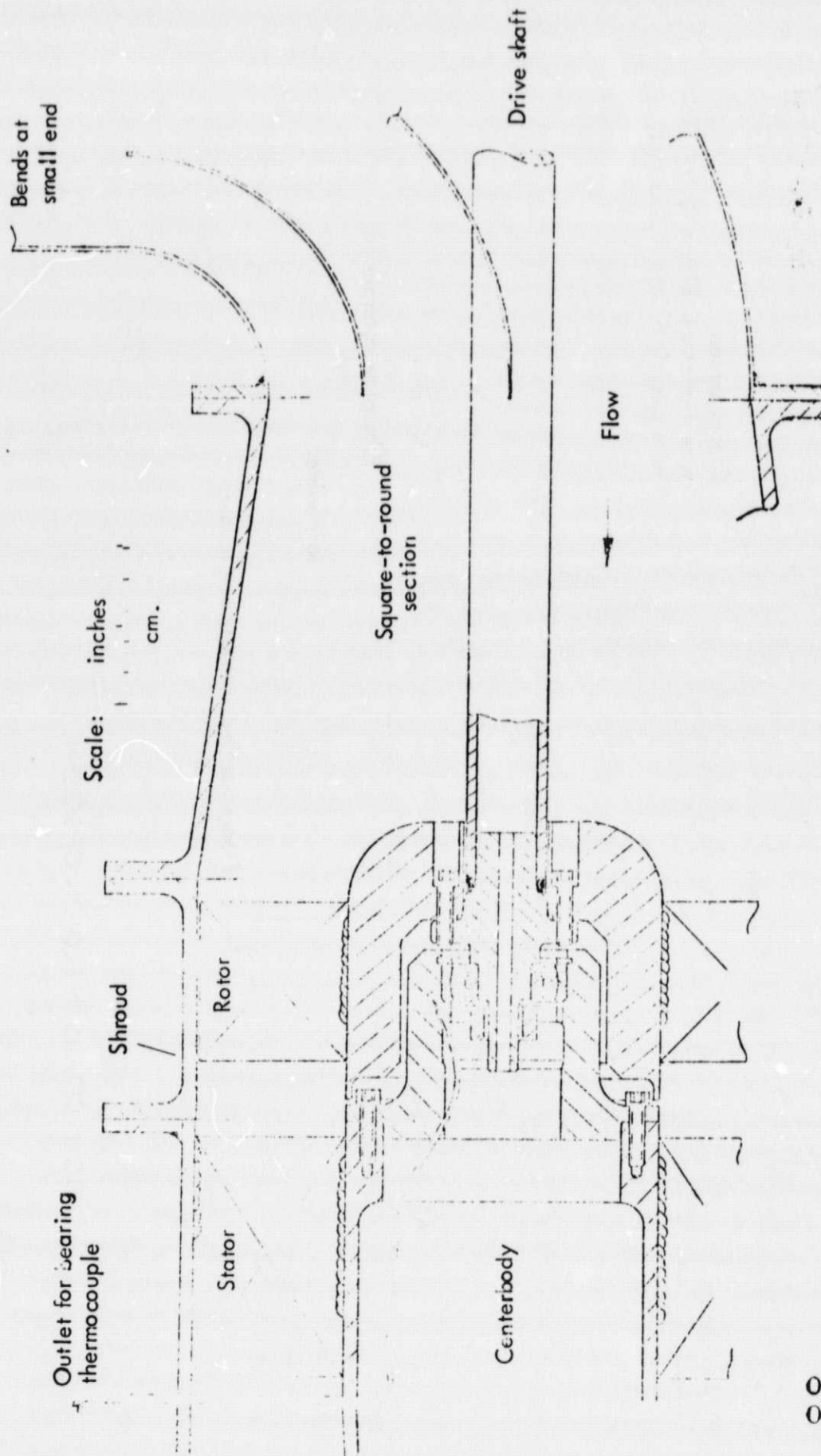


FIG 6. CROSS SECTION THROUGH FAN AND TURNING VANES AT SMALL
END OF CIRCUIT.

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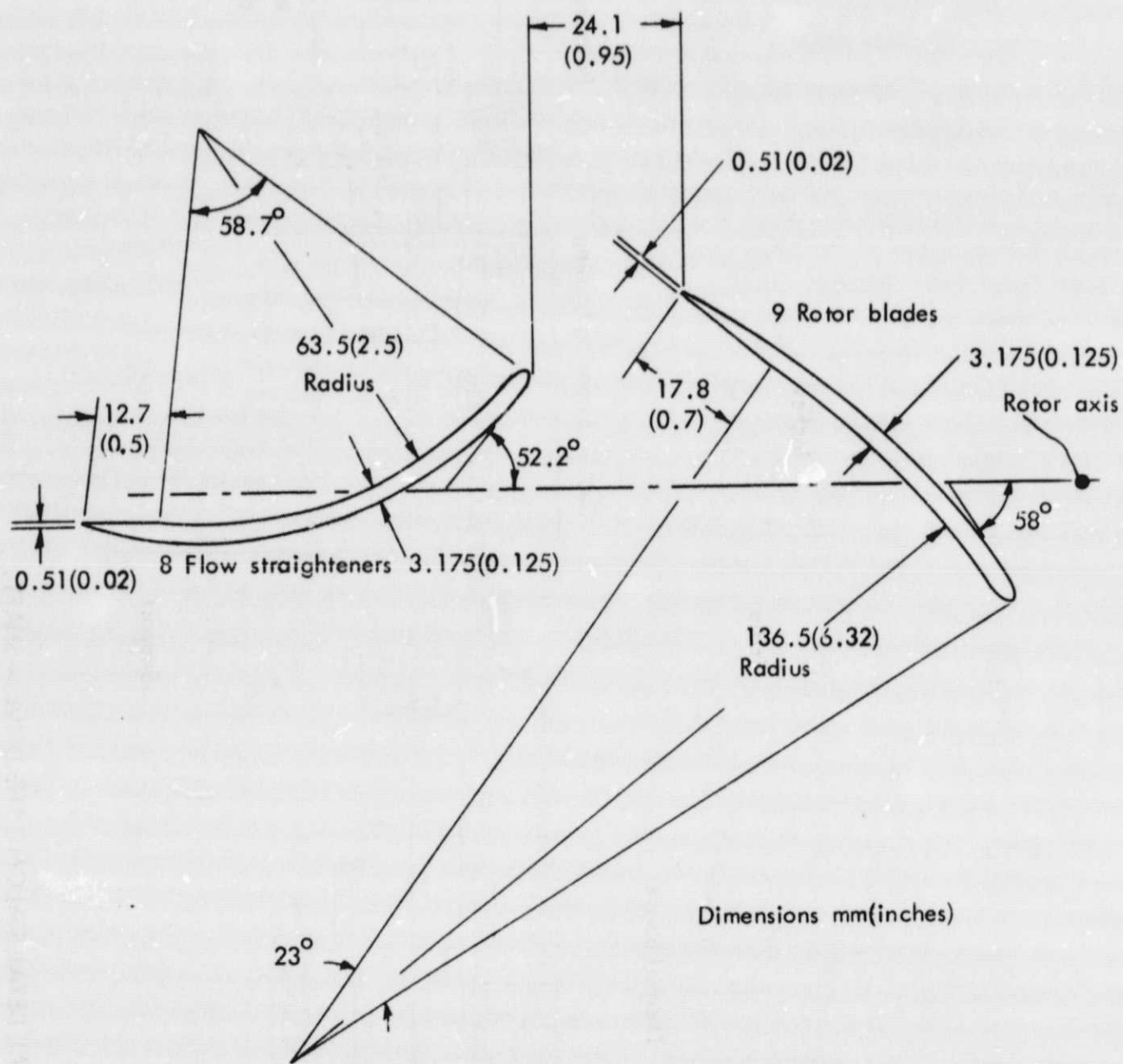


FIG 7. GEOMETRIES OF ALUMINUM ROTOR AND STATOR BLADE CROSS SECTIONS. BLADES ARE UNTWISTED.

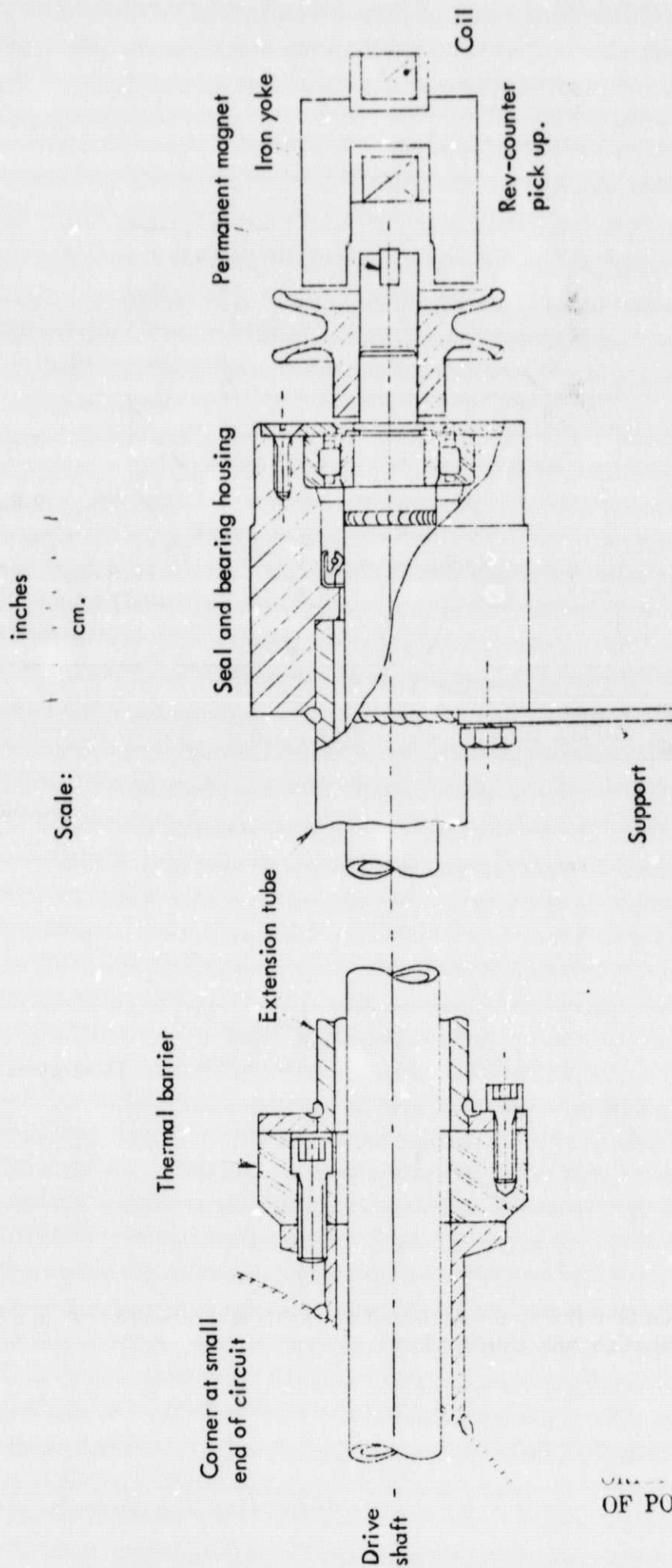


FIG 8. MECHANICAL DETAILS ALONG THE DRIVE - SHAFT.

KEY	T_o	Stagnation temperature
	P_o	Stagnation pressure
	T	Temperature
	P	Static pressure
	RPM	Fan rotational speed

4 (T_o, P_o, P) TRAVERSE

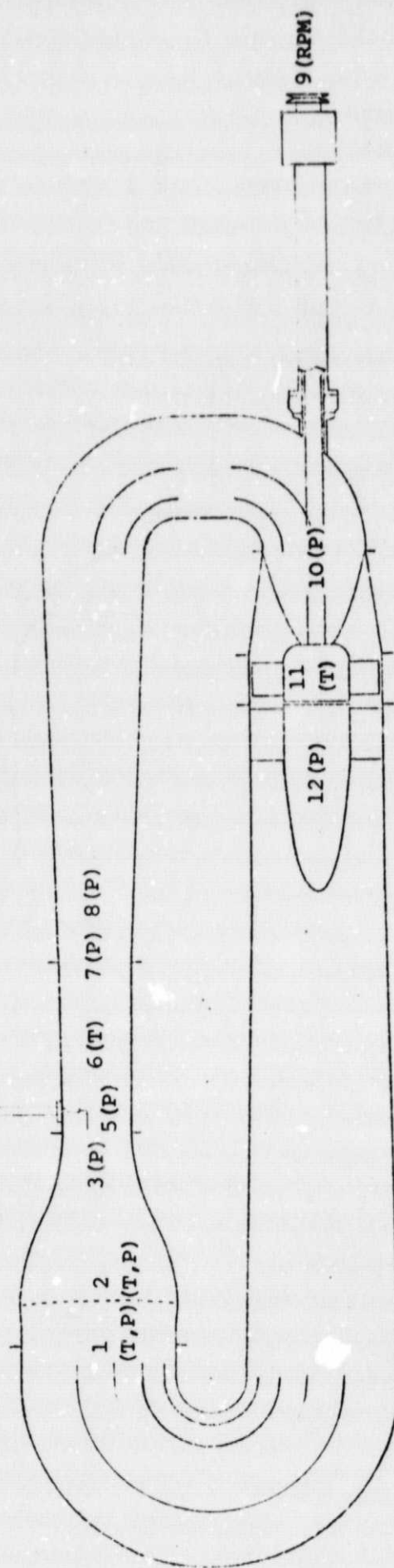


FIG 9. LOCATION OF INSTRUMENTATION SENSORS.

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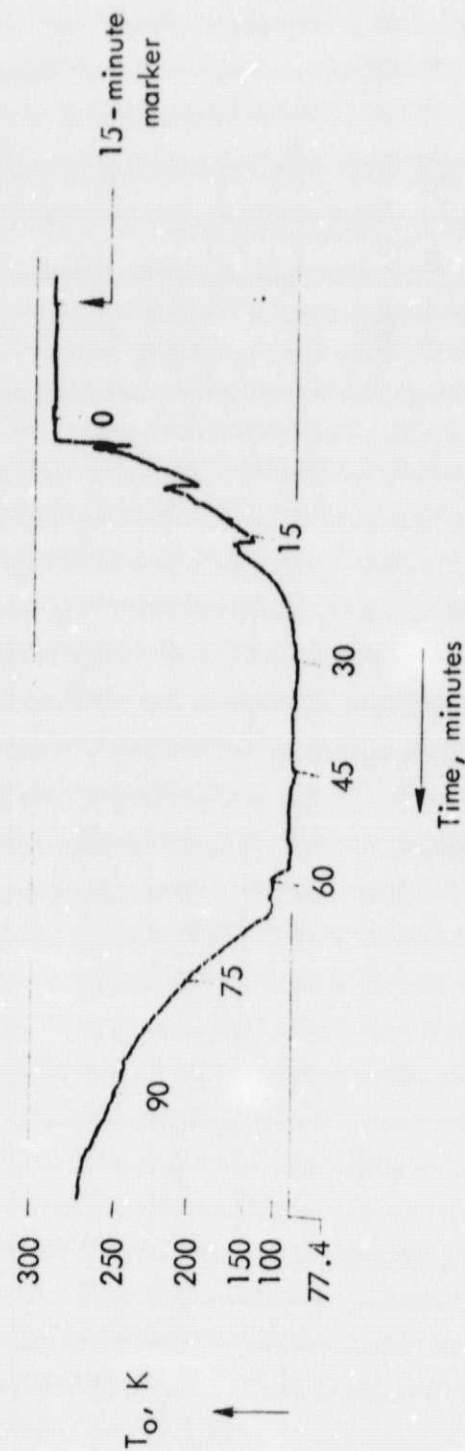


FIG. 10 THE TEMPERATURE - TIME RECORDING OF AN EARLY RUN OF THE 0.1m CRYOGENIC TUNNEL.

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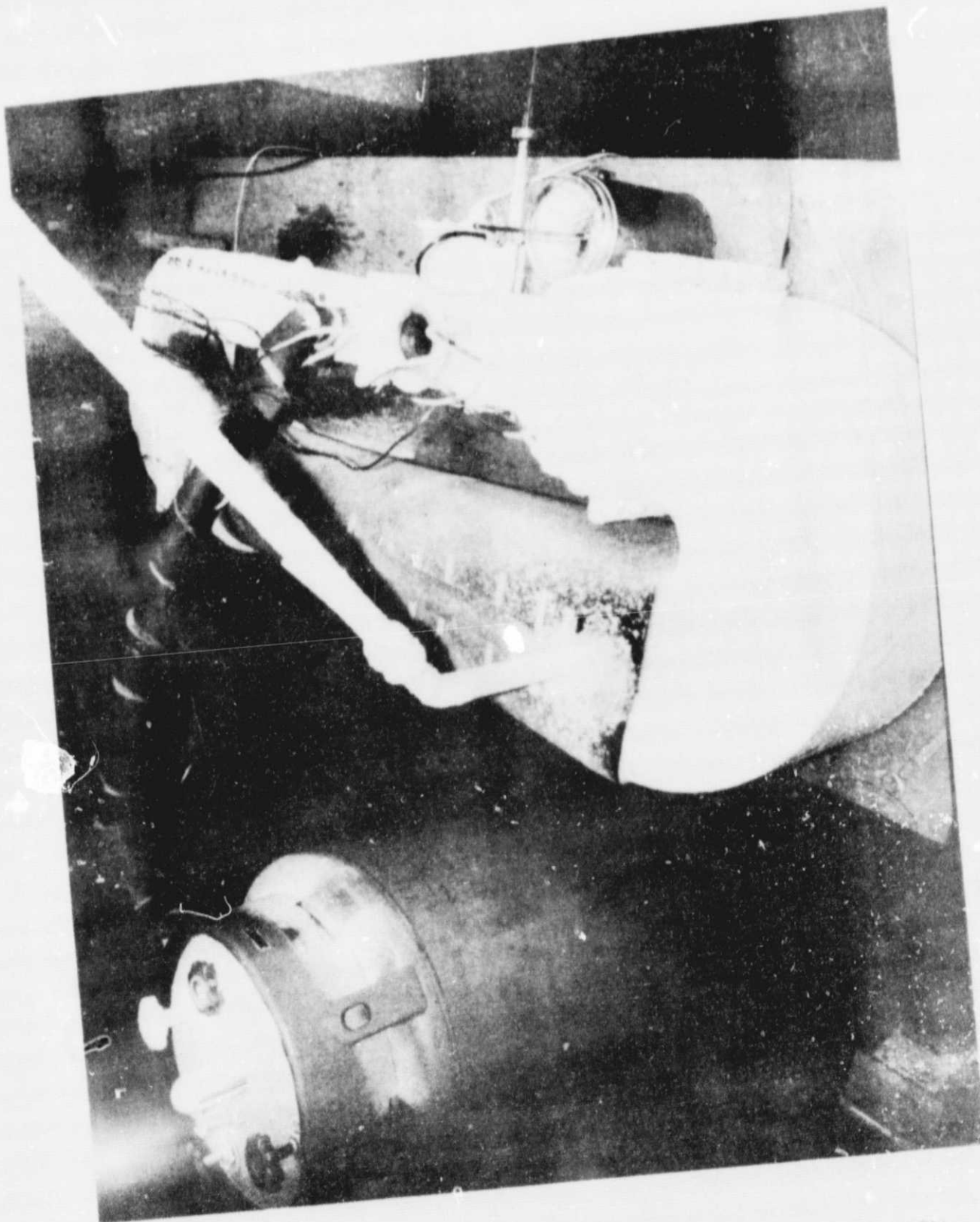


FIG.11 THE 0.1m CRYOGENIC TUNNEL AT UNIVERSITY OF SOUTHAMPTON.

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Unit Reynolds number
millions per meter

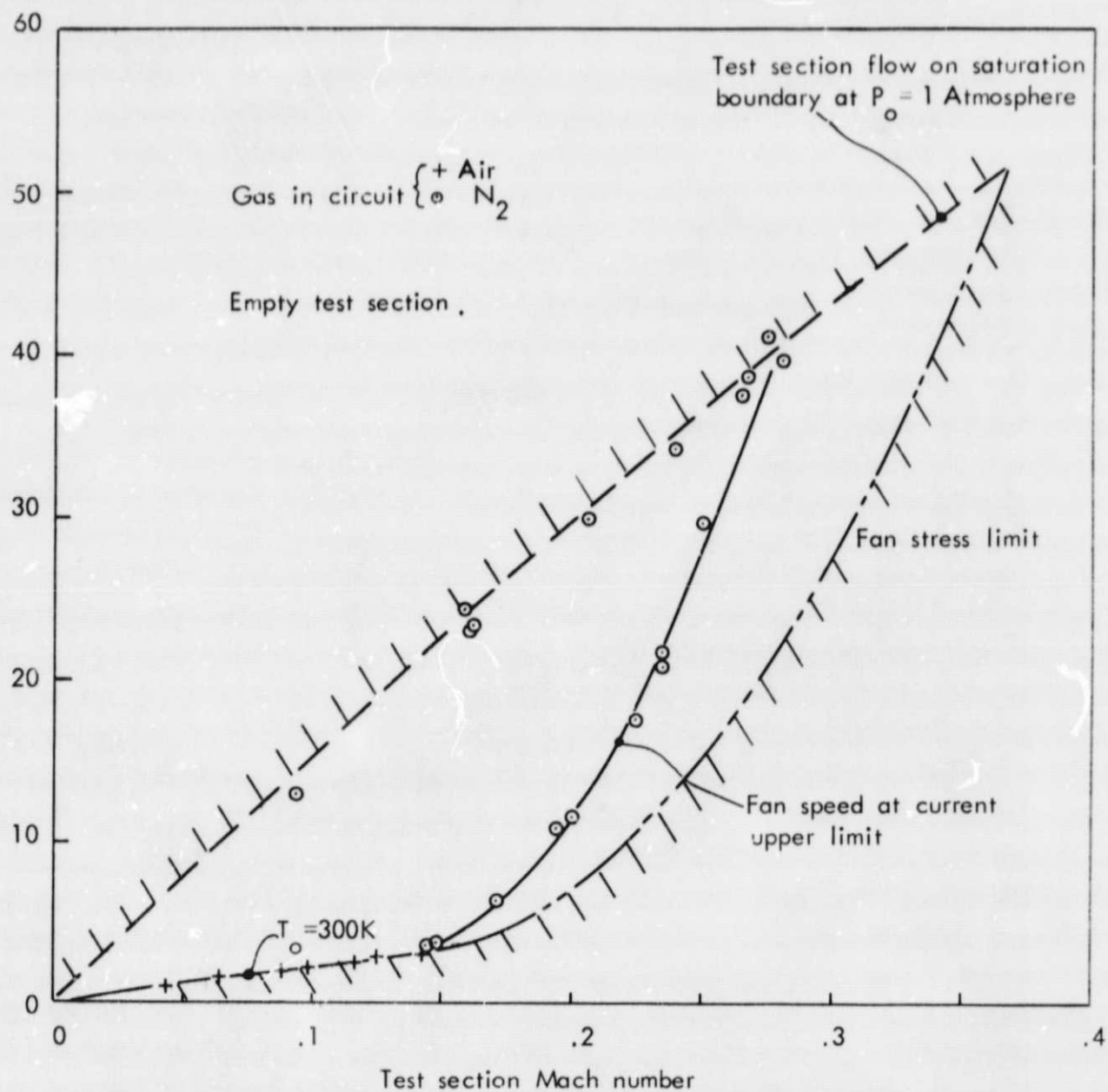


FIG 12. DESIGN OPERATING ENVELOPE OF 0.1 m CRYOGENIC WIND TUNNEL WITH DATA POINTS SHOWING THE EXTREMES OF THE ENVELOPE EXPLORED TO DATE.

Data taken at room temperature in air, at $M \approx 0.09$

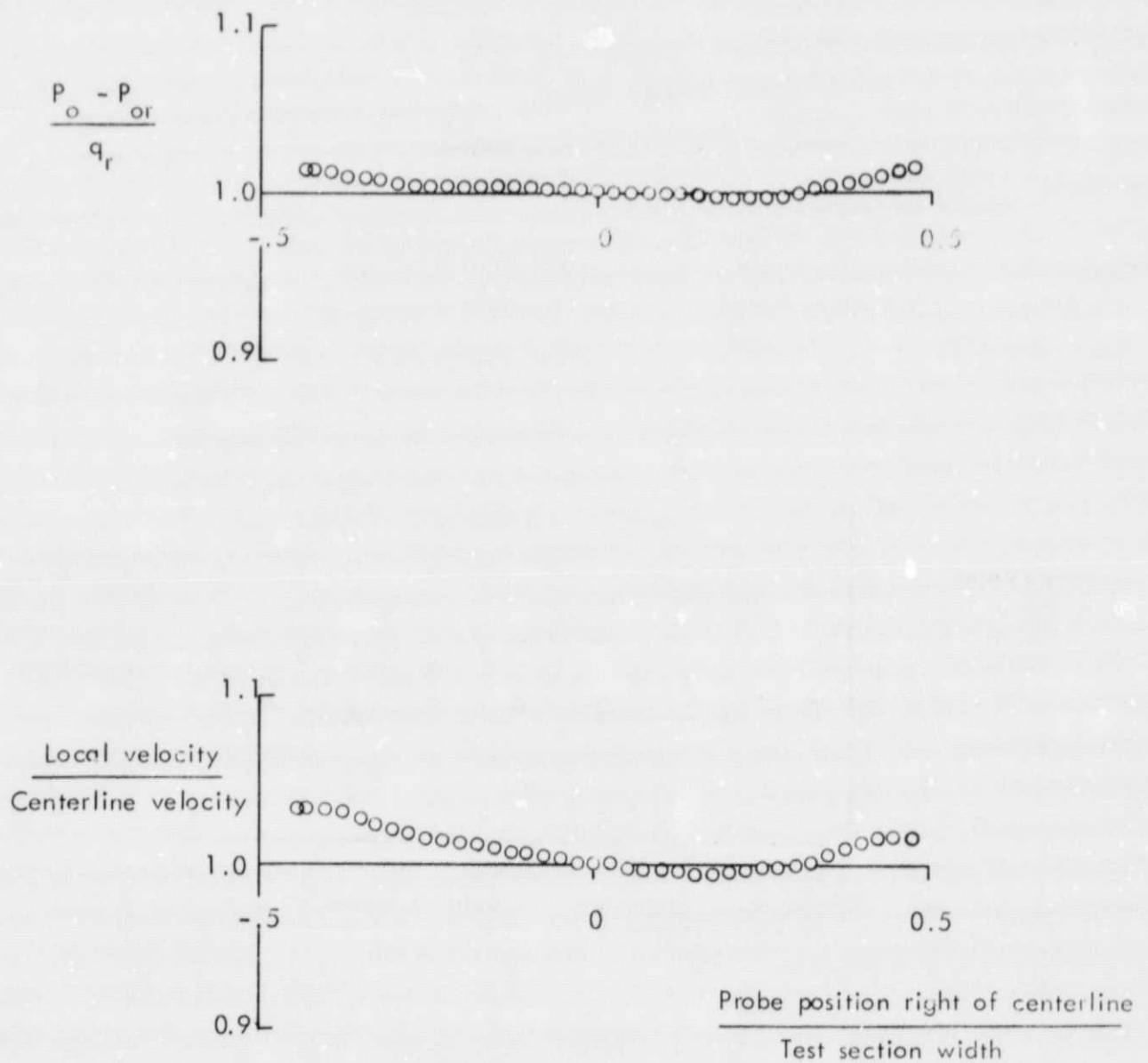


FIG 13. STAGATION PRESSURE AND VELOCITY DISTRIBUTIONS ALONG A MID-HEIGHT HORIZONTAL LINE ACROSS THE UPSTREAM END OF THE TEST SECTION.)

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Data taken in N_2 at $M \approx 0.13$

Mean centerline temperatures :

○ 79.4 K

+ 85.1 K

△ 110 K

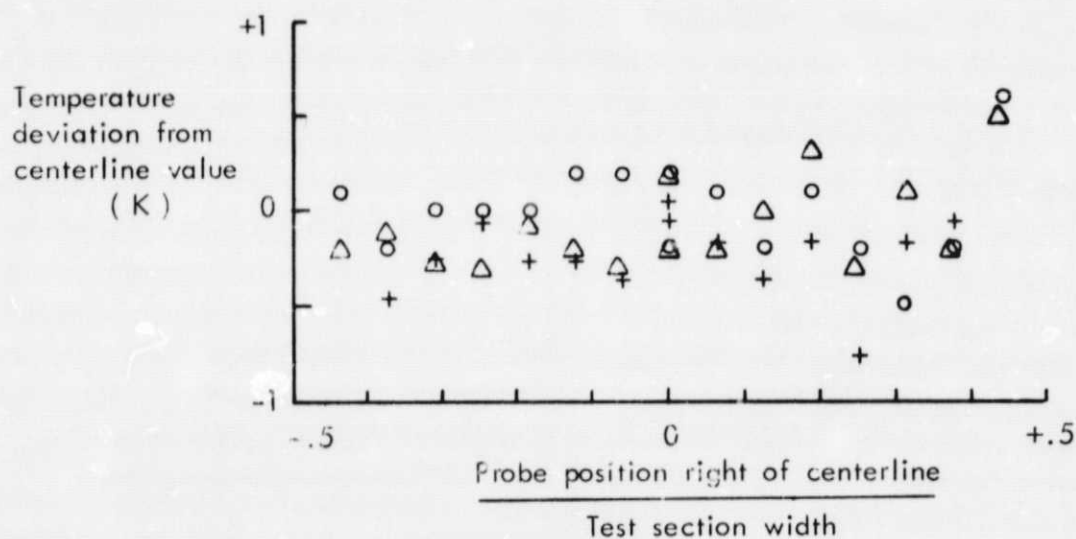


FIG 14 TEMPERATURE DISTRIBUTIONS ALONG A MID-HEIGHT HORIZONTAL LINE ACROSS THE UPSTREAM END OF THE TEST SECTION.

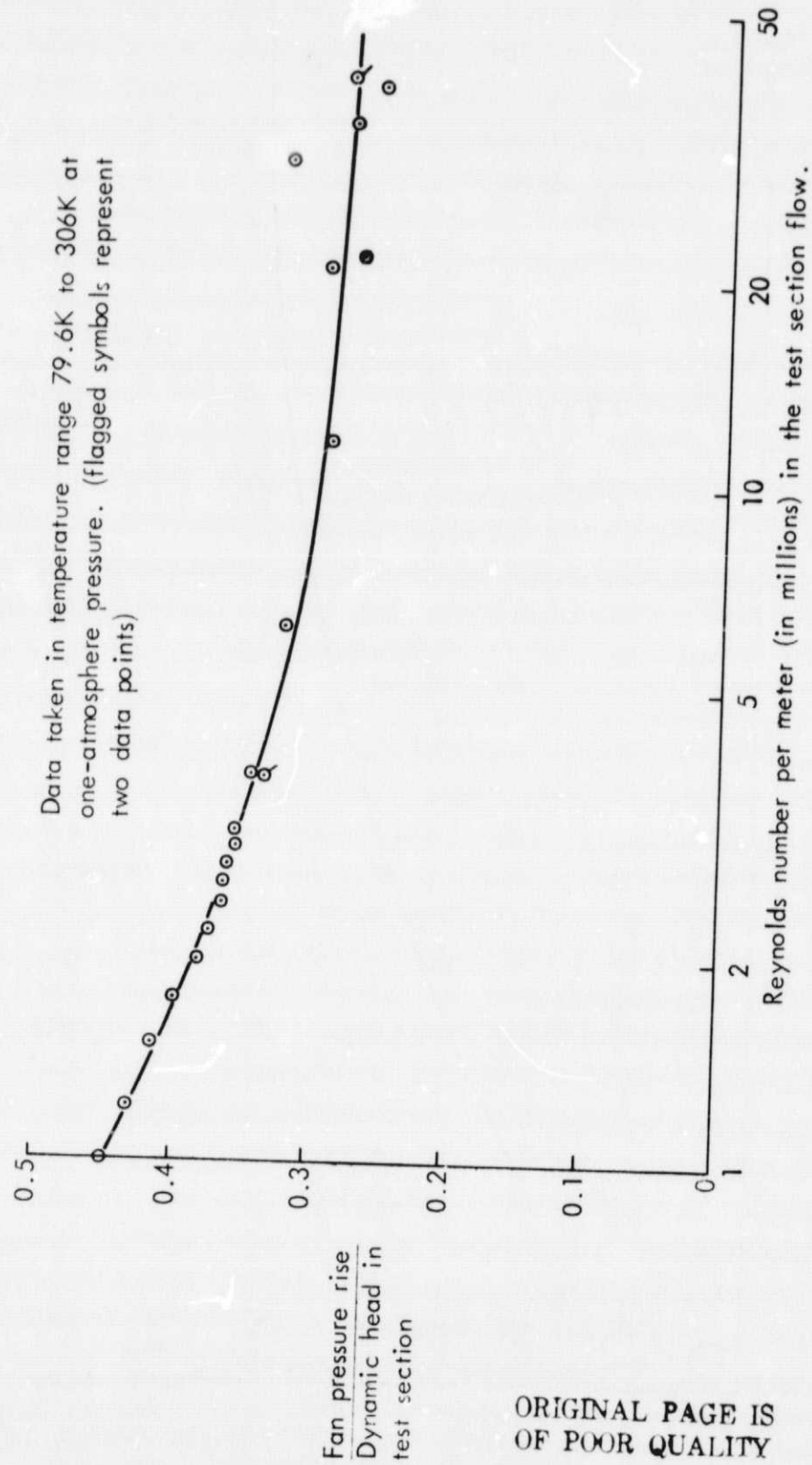


FIG 15. A NON-DIMENSIONAL MEASURE OF FAN PRESSURE RISE AS A FUNCTION OF TEST SECTION
 UNIT REYNOLDS NUMBER.

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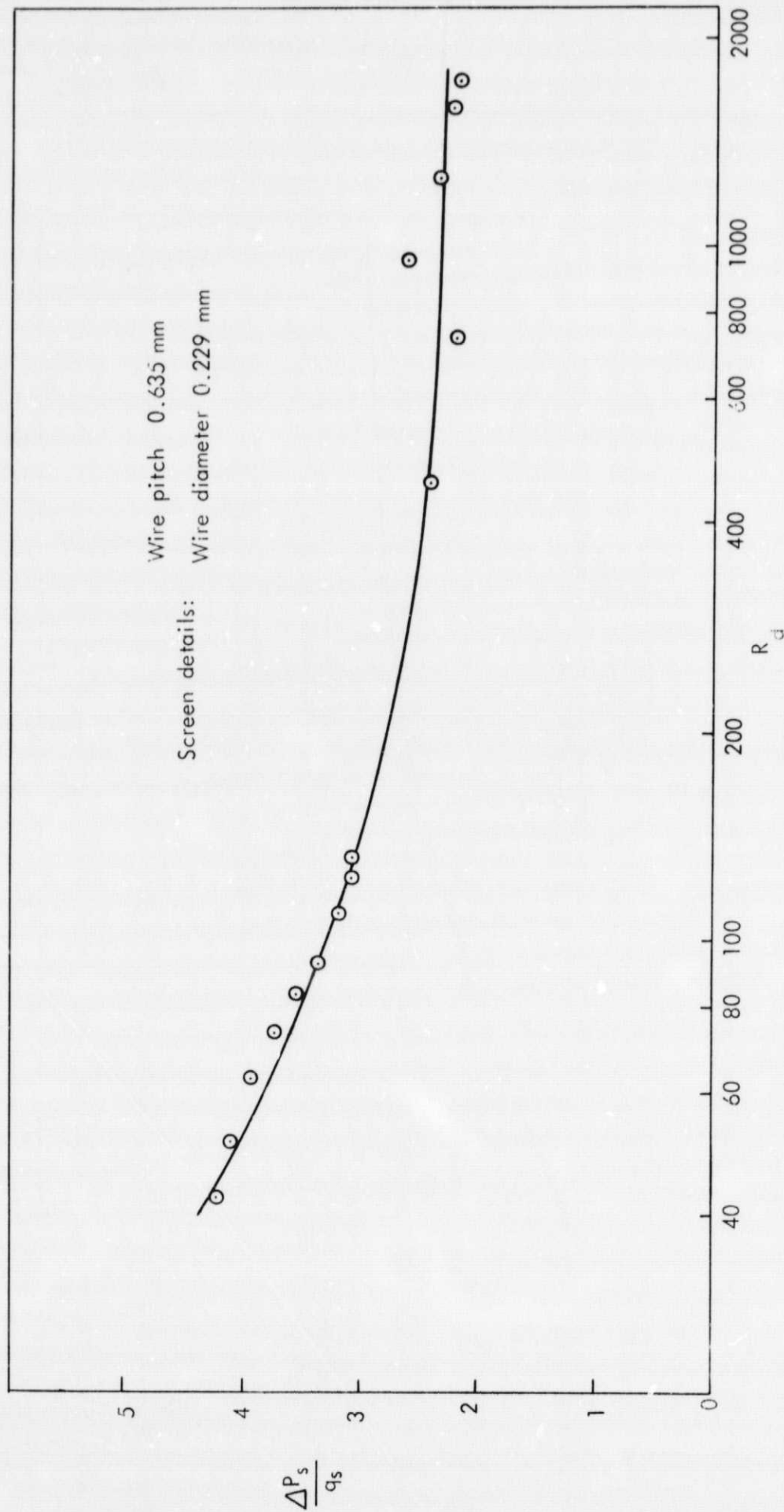


FIG 16 SCREEN PRESSURE LOSS COEFFICIENT $\frac{\Delta P_s}{q_s}$ AS A FUNCTION OF REYNOLDS NUMBER R_d BASED ON WIRE DIAMETER